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Natural and human controls of water quality of an Amazon estuary (Caeté-PA, Brazil)

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Abstract

Estuarine waters are usually eutrophic due to nutrients input derived from natural and anthropogenic sources. In the Caeté Estuary, nutrients and thermotolerant coliforms input is intensified by the absence of a public sanitation system and by mangrove outwelling. This input is more accentuated in the upper sector of the estuary where 90% of the local population is concentrated and a high incidence of commercial activities (public markets, ice factories and boat repairing among others) is located. As a consequence, eutrophic waters with high concentrations of thermotolerant coliforms (up to 1100 MPN/100 ml) were observed during the dry season when dilution and/or advection are less effective. Eutrophication, though less pronounced, also occurred in the other sectors (middle and lower), but these results seem to indicate that this could be a natural condition of an Amazon region which is naturally enriched with a high amount of nutrients. On the other hand, nutrient concentration values in the upper sector are similar to those found in other highly populated and industrialized Brazilian estuaries. Taking into account that the population increases by about 20% per decade in the region, this growth may lead to a significant increase in human pressure and impacts on the area, mainly during periods when the estuary is more susceptible to retaining nutrients (e.g., during the dry season). In order to improve water quality, the DPSIR framework was used as a guide for proposing potential measures to be implemented in the Caeté Estuary based on (i) urban planning to control sewage discharges, (ii) construction of water treatment infrastructures to reduce untreated effluents inputs and (iii) water use regulations as a function of the current water quality.

Key-words: eutrophication, sewage outfall, mangrove outwelling, trophic status.

1. Introduction

Estuaries are some of the most attractive coastal environments for human occupation because they have enormous potential for the development of several economic activities, such as agriculture, aquaculture, harbour and touristic activities (Kennish, 2002 and Dias et al., 2013). Consequently, during recent decades, estuaries worldwide have been affected by rapid population growth, which has led to unregulated urban expansions and the corresponding effects of multiple human activities (Lindeboom, 2002; Elliot and Quintino, 2007; Dias et al. 2013). As a result of excess nutrient inputs from anthropogenic sources, also known as *cultural eutrophication* (Hasler, 1947), one of the major and most commonly associated environmental problems in these areas is the decrease in water quality.

Estuarine waters are usually eutrophic due to land-derived nutrients (Janelidze et al. 2011; Majewska et al. 2012), and anthropic influences (e.g., the lack of an adequate public sanitation system) can contribute to an increase in the input of inorganic nutrients and organic components (Howarth and Marino, 2006; Burford et al. 2012). High dissolved nutrient concentrations generated by natural and/or anthropogenic causes can result in negative consequences, such as: (i) the increase of particulate organic matter and water turbidity; (ii) the occurrence of phytoplankton and microphyte blooms which may be responsible for the reduction of concentrations of dissolved oxygen in the water, inducing the mortality of some organisms, and (iii) the decrease of local biodiversity (Roberts and Pierce, 1974; Anderson et al. 2002; Karlson et al. 2002; Burford et al. 2012).

Cultural eutrophication has been detected in estuaries worldwide, from developing to developed countries (e.g., China, India, Brazil, Russia, United States, and Australia) (Fisher et al. 2006; Martin et al. 2008; Santiago et al. 2010; Aleksandrov, 2010; De et al. 2011; Cheng et al. 2012). In order to reduce this impact on estuarine environments, countries are progressively adopting measures to decrease nutrient loads from point and diffuse sources. The building of sewage treatment plants is the most common of these measures (Greening and Janicki, 2006).

In Brazil, although the situation is progressively improving, the current public sanitation system is precarious, with less than 40% of the total domestic sewage being treated (IBGE, 2000). In the northern Brazilian coast (known as the Amazon coast), the situation is even worse, since the lack or the inefficiency of a public sanitation system occurs in practically 100% of local cities. Moreover, this coast is located at the edge of the largest and one of the best-preserved tropical rainforests in the world with the largest continuous mangrove system on the planet (Kjerve and Lacerda, 1993). It occupies approximately 35% of the Brazilian coastline and is characterized by the presence of dozens of estuaries, including the Amazon River Estuary. This estuarine–marine system is also responsible for one of the largest run-off of sediments, dissolved nutrients, and organic material found on Earth (Geyer et al. 1996). Thus, eutrophication in this area can occur due to natural processes (e.g., outwelling from mangroves) and/or human processes (e.g. the presence of wastewater outfalls) (Menezes et al. 2009; Gomes et al. 2011).

Within this context, we analyze in this study the environmental quality of the Caeté Estuary where Bragança city is located, a 400 year-old historical city. The area is naturally influenced by the presence of an important mangrove area, and anthropogenically, by the existence of several sewage outfalls, mainly in the upper estuarine sector. In this sense, this work can be considered as a good case study for assessing the potential effects of expanding human settlements in these natural environments. Thus, the main goal of this work is to identify how natural characteristics of the region and anthropogenic activities surrounding the estuary influence the water quality.

2. Study Area

The Caeté Estuary is part of the Amazon estuarine system in Pará, NE Brazil (Figure 1). It consists of numerous channels that branch off and form the main mangrove peninsula. The main channel has a meandering form with a length of more than 40 km, and a width of 150 m at its southernmost limit and 4,600 m at the mouth (the Atlantic Ocean) (Guerra and Cunha, 1998). It can be classified as a well-mixed, permanently open, turbid, and shallow estuary, with a maximum depth of about 10 m (Dittmar et al. 2001; Barletta-Bergan et al. 2002).

The climate of the area is classified as equatorial humid, with a *wet season*, between January and June, when total rainfall often exceeds 2,000 mm, and mean temperatures are around 26ºC to 27°C, and with a *dry season*, from July to December, when monthly mean rainfall is below 100 mm, and mean temperatures are around 28ºC to 30°C (Martorano et al. 1993; INMET, 2009).

<insert Figure 1>

The area is subjected to semi-diurnal tides, with a 4-6 m tidal range during spring tides, and a 2-4 m range during neap tides (Cohen et al. 1999; Pereira et al. 2009, 2010). Fortnightly, the tidal water reaches the highest levels in the mangrove forests and as a result dissolves solutes and other nutrients, transferring them into the estuary (Cohen et al. 1999; Pereira et al. 2010; Monteiro et al. 2011).

The estuary is part of the Caeté-Taperaçu Marine Extractivist Reserve. It is a valuable and productive ecosystem, surrounded by a broad range of coastal environments, including salt marshes, tidal sand flats, coastal sand dunes, barrier sand ridges, creeks, and ebb tidal deltas, providing a wide variety of benefits to humans in the form of ecosystem services and functions.

The estuary is located at the Caeté hydrographic basin, which covers a total area of 2,195 km², where about 300,000 people live (IBGE, 2010). About 27% of this population (80,585 inhabitants) is concentrated along the estuarine sector in the municipality of Bragança. The city's economy is based mainly on fishing, commerce, and tourism (IBGE, 2010). It occupies the third position in marine-origin fishery production in the state, which is the largest extractive fish producer of Brazil (CEPNOR - IBAMA, 2005). According to Krause and Glaser (2003), Glaser and Diele (2004), Gorayeb et al. (2009) and Guimarães et al. (2011), the principal economic activities of the local rural population are related to the sustainable use of natural resources, particularly fishing (crabs, mollusks, and fish) and agriculture (rice, beans, and açaí).

3. Material and Methods

The study area was surveyed from April 2006 to February 2007, when rainfall, river discharge, tides, currents, and river hydrological data (i.e., dissolved nutrients, chlorophyll *a* and thermotolerant coliforms) were acquired.

Rainfall and wind speeds were recorded daily by the Brazilian Meteorology Institute – INMET (-1.06º S -46.9º W), while river discharge data was obtained from the Brazilian Water Agency – ANA (-1.16º S -46.5º W).

Hydrodynamic and hydrological conditions were monitored during six field campaigns undertaken between April 2006 and February 2007. Each campaign was conducted during the spring tide over a 25-h period in three sectors of the estuary which are subject to different levels of human influence. The upper sector (St3, about 40 km upstream the estuarine mouth) is characterized by a high human influence. With about the 90% of the total estuarine population (72,621 inhabitants), this sector concentrates main services available in the region (markets, hospitals, fishing and ice factories and boat repairs among others). On the other hand, the middle (St2, about 20 km upstream the estuarine mouth) and lower sectors (St1, in the estuarine mouth) are representative of low direct human pressure: a fish processing plant (GPesca Ltda.) and two ice factories in the middle sector are the main human elements.

The magnitude of sewage effluents produced by the local population was estimated by assuming that each inhabitant produced a minimum of 150 l per day of sewage effluents containing 54.0 g of DBO, 8.0 g of Nitrogenous and 2.5 g Phosphorous compounds (ABNT, 1993; Von Sperling, 1996).

Water samples were obtained by using a Niskin bottle every 6 h at 3.0 m below the surface at the three sectors mentioned above (Figure 1). Simultaneously, current speeds were measured every 10 min using a mini-current meter (Sensordata SD 6000). The water level was measured by using a tide gauge located between the upper and middle reaches of the estuary at the same interval of 10 min (Figure 1). Tidal records representative of conditions at the outer part of the estuary were obtained at the Salinópolis station from the Hydrographic and Navigation Department (DHN) of the Brazilian Navy.

Water microbiological conditions were determined by means of the multiple tube fermentation technique (APHA, 1992), and results were evaluated in accordance with the criteria of the *Brazilian Ministry of Environment* - CONAMA (Ordinance nº 274/2000). In this study, thermotolerant coliform concentrations were used as an indicator of anthropic pressure due to sewage outfalls.

Salinity was measured with a salinity meter and dissolved nutrients (phosphate-PO_4, nitrite-NO2 and nitrate-NO_3) were analyzed according to the Strickland and Parsons (1972) and Grasshoff et al. (1983) methods. Chlorophyll *a* concentrations were estimated by the Parsons and Strickland (1963) and UNESCO (1966) methods. All collected data were analyzed according to spatial (different sectors of estuary) and seasonal (wet and dry periods) variations.

To characterize the trophic status of the estuary two trophic indexes were used. The Karydis index, *TI*, is calculated as (Karydis et al, 1983):

$$TI = \frac{C}{C - \log x} + \log A$$

where, *C* is the log of the total loading of nitrates in an area, *x* is the total concentration of nitrates at a given station, and *A* is the number of stations. Score values provide a continuous assessment of water quality: *TI* values larger than 5 indicate eutrophic waters; mesotrophic waters are indicated by values between 3 and 5, and values lower than 3 correspond to oligotrophic conditions. The nitrate level was selected to determine the *TI* index because it is considered the best indicator of water quality in areas affected by wastewater because nitrates dissolve quicker than other nutrients (APHA, 1992).

The TRIX index was developed by Vollenweider et al. (1998) and it is given by:

$$TRIX = (\log_{10} [Chl\ a \times (DO_2\%) \times DIN \times DIP] + k) / m$$

where Chl *a* is the chlorophyll *a* concentration, $DO_2\%$ is the oxygen saturation rate, DIN is the dissolved inorganic nitrogen, and DIP is the concentration of dissolved inorganic phosphorus. k and m are constants with values of 1.5 and 1.2 respectively. Water is classified according to the following scale: (i) 0 - 4: low eutrophication level and high water quality; (ii) > 4 - 5: medium eutrophication level and good water quality; (iii) > 5 - 6: high eutrophication level and bad water quality and, (iv) > 6 - 10: elevated eutrophication level and poor water quality.

4. The behavior of the Caeté Estuary

4.1 Physical processes

The cumulative precipitation during this period reached 2,171 mm which is in the same order of magnitude of normal conditions for the Bragantinian region (long-term averaged annual rate of about 2,500 mm, INMET). Rainfall reflected the typical climate seasonality of the area, with two well-defined seasons: wet and dry (Figure 2). The wet season extended from January 2006 to July 2006, when the 92% of the annual rainfall occurred (total rainfall of 2,000 mm). Months with the lowest rainfall ranged from August 2006 to January 2007, with a total precipitation of 171 mm (8%

of the annual rainfall). The wettest and driest months were March (465 mm) and October (1 mm) of 2006, respectively.

Hydrodynamic conditions in the estuary are controlled by the river discharge and tides. The highest river discharge was 82.5 m^3/s, and it was recorded in April 2006, at the peak of the wet season, whereas a minimum discharge of 3.0 m^3/s was measured at the end of the dry season (January 2007) (Figure 2).

<insert Figure 2>

Water levels in the estuary varied between 4.2 m and 4.9 m at the upper sector and from 4.1 to 4.6 m at the lower sector. The largest tidal range was recorded during the dry season (August), whereas the smallest range was registered during the wet season (June). The tidal range increased in the upstream direction along the estuary between 0.10 and 0.40 m due to the narrowness of the channel in the middle sector. Tide propagation through the estuary is asymmetric, with an ebb period (6.3 to 8.3 h) that is longer than the flood period (3.8 to 6.0 h). The tidal asymmetry is lower during the dry season when the river discharge is the lowest.

In general, the highest mean current velocities were recorded at the middle estuary (Figure 3), probably due to the presence of sand banks which narrow the estuarine channel. Observed seasonal differences in current velocity reflected variations in river discharge. During the wet season, the highest river discharge resulted in the largest ebb current velocities, which were recorded at the upper sector (around 1.0 m/s). During the dry season, the increase of the relative influence of marine processes due to low river discharges contributed to higher flood currents at the lower estuary, principally in October (0.7 m/s) and in December (0.9 m/s).

Moreover, during this period, constant winds blowing towards the land were dominant in the region, with average monthly values ranging from 3.0 to 4.0 m/s. These winds have induced a landward flow at the estuary mouth, contributing to the observed increase in flood current velocity.

<insert Figure 3>

4.2 Hydrological processes

At the upper sector, the lowest salinity (around 0) and dissolved nutrient concentrations were recorded during the wet season (1.2 µm of nitrate-NO_3, 0.1 µm of nitrite-NO_2, and 0.3 µm of phosphate-PO_4), most likely reflecting a larger dilution due to high river discharges. Moreover, we would expect that the long ebb tidal cycle (minimum of 8.0 h) and strong ebb currents observed in this period, would enhance the downstream advection of nutrients, directing them towards the middle and lower sectors. We observed that during the wet season, these downstream sectors presented slightly higher nutrient concentrations (maximum of 8.4 µm of nitrate-NO_3, 0.7 µm of nitrite-NO_2, and 1.0 µm of phosphate-PO_4 in the middle sector; and 9.6 µm of nitrate-NO_3, 0.5 µm of nitrite-NO_2, and 0.7 µm of phosphate-PO_4 in the lower sector) (Figure 4).

During the dry season, the low river discharge contributed to an increase of salinity values (around 10) due to the higher marine intrusion into the estuary and to a lower dilution of effluents released in the upper estuary. As a consequence, dissolved nutrient values (mainly nitrogenous), increased in the upper sector (maximum of 35.6 µm of nitrate-NO_3 and 2.8 µm of nitrite-NO_2). On the other hand, the transport from upper to middle and lower sectors during ebb tide cycle was reduced (maximum ebb tide period in the upper sector 7.5 h) in such a way that a better water quality was observed in these sectors (a maximum of 12.9 µm of nitrate-NO_3, 2.6 µm of nitrite-NO_2, and 3.3 µm of phosphate-PO_4 in the middle sector; and 11.5 µm of nitrate-NO_3, 0.4 µm of nitrite-NO_2, and 0.9 µm of phosphate-PO_4 in the lower sector) (Figure 4). In addition, the large tidal range recorded during the dry season should favor the inundation of mangrove areas adjacent to the estuary. This increase in inundation would enhance the mangrove outwelling, with a corresponding increase in nutrient inputs to the estuary.

The high chlorophyll *a* concentrations recorded (between 3.9 mg/m^3 and 17.6 mg/m^3) demonstrated the high productivity of the system. Observed values did not show any clear seasonal pattern, however, values tend to increase near the sewage outfalls in the upper sector (Figure 4) during wet season.

<insert Figure 4>

4.3 Trophic Index

Figure 5 shows calculated trophic conditions along the estuary during the monitoring period. Eutrophic conditions were frequent in the Caeté Estuary, indicating its high biological productivity. As was expected, the index presents the same spatial and seasonal trends as those observed for dissolved nutrients.

During the wet season, the upper sector presents the mesotrophic condition due to the aforementioned downstream transport to middle and lower sectors that reached poorer conditions (eutrophic). In contrast, during the dry season, the upper sector presented the largest values of the trophic index (eutrophic), whereas the downstream sectors tended to present mesotrophic conditions (Figure 5). Results obtained by using the TRIX index also indicated the worst conditions during the dry season in the upper estuary, corresponding to poor water quality and elevated eutrophication. In the lower estuary, no significant seasonal variations were detected, with elevated eutrophication being indicated in both seasons (Figure 5). During the dry season, both indexes predicted high eutrophicaton at the upper sector of the estuary, indicating that, during this period, estuarine dynamics was insufficient to naturally depurate the excess of nutrients in the water column.

<insert Figure 5>

4.4 Bacteriological State

Figure 6 shows the variation of measured thermotolerant coliform concentrations along the Caeté Estuary during the monitoring period. With the exception of the April campaign (wet season), the highest concentrations measured occurred at the upper sector, with the sampling taken in February 2007 (end of the dry season) being the largest recorded value (>1100 NMP/100 ml), a value about 5 times higher than that of the lower estuary (<240 MPN/100 ml). This pattern would reflect the negative impact caused by untreated sewage effluents released in the upper sector of the estuary. This seasonal behavior is consistent with the observed pattern in dissolved nutrients, in which case concentrations in the upper sector drastically increased during the dry season and decreased during the wet period.

Applying the criteria of the *Brazilian Ministry of Environment* for brackish water environmental quality standards (CONAMA - resolution nº 274/2000), the water quality in the Caeté Estuary was *good* during the wet season. However, during the dry period, the water quality was *inadequate* for aquaculture, human supply and, even, primary contact. Observed values during the dry season were 4 times higher than accepted standards established by CONAMA criteria.

<insert Figure 6>

5. Human vs natural dimensions

The previously described behavior of the waters of the Caeté Estuary is the result of the balance between natural system dynamics, which is governed by the river discharge and tidal dynamics, and human forcing, which alters natural conditions. Both components are put into context in what follows.

5.1 Human forcing

In recent decades, unplanned urban development associated with rapid population growth, the absence of efficient public policies, and associated human activities have caused serious social and environmental problems in the Caeté river basin (Gorayeb et al. 2011; Guimarães et al. 2011).

The population in the Bragantinian region has grown significantly during the second half of the XXth century, with an increase of about 200% between 1940 and 2010. In 2010, the total number of inhabitants in Bragança city and in small villages surrounding the Caeté Estuary was around 80,585 (IBGE, 2013), with about 90%

(72,621 inhabitants) living in the upper estuarine sector. The remaining inhabitants live in small villages located at the middle (7,672) and lower (292) sectors.

Fishing is the main economic activity in the area, and is one of the main sources of sewage pollution in the estuary. Associated activities, such as ice factories, fishing factories, fishing markets, and boat repairs (boat docks), are located along the estuary. In the middle sector of the estuary one of the most important fish processing plants of the state of Pará (GPesca Comercial Ltda.) has been operating since 2002. This plant produces a daily average of 130 m^3 of liquid effluents, which are treated before being released to the Caeté Estuary. Estimations of the total volume of BOD (biological oxygen demand) and nutrients discharged into the Caeté Estuary per day are shown in table 1. Unfortunately, difficulties in getting water consumption data from other local industries does not permit the quantification of the total amount of effluents released to the estuary.

The most intense development of agriculture in the Caeté river basin is mainly concentrated in the high and middle sectors. In spite of this, previous studies carried out by Gorayeb et al. (2009) did not observe a significant influence of this activity on the river water quality. Along the estuarine part of the Caeté River (lower reach of the hydrographic basin), agriculture is essentially implemented at small scale (subsistence agriculture). Due to this difference in the scale of development, and extrapolating observations in the upper parts, we can assume that the influence of agriculture on the water quality of the estuary is low.

<insert Table 1>

One of the main consequences of the unplanned urban development has been the absence of sewage treatment systems, which has become the principal agent affecting Caeté estuarine waters (Guimarães et al. 2009; Pereira et al. 2010, Monteiro et al. 2011). As a result of this, the Caeté Estuary receives direct sewage inputs or those transported by sewer networks (Gorayeb et al. 2009). The most important direct sewage outfalls along the estuary are shown in Figure 1.

In order to estimate the order of magnitude of potential pressure, if we apply the Brazilian Standard for water treatment (ABNT/NBR-7229, 1993) the population situated along the Caeté Estuary (without considering industrial activities) should produce about 12,000 m^3 per day of sewage effluents. This corresponds to an equivalent production of 5.4 tons of DBO, 0.6 ton of nitrogen and 0.08 tons of phosphorous. Due to the lack of water treatment plants, these effluents are not receiving the treatment recommended by the CONAMA criteria (Resolution nº 274/2000), and they are discharged directly into the estuary.

In addition to this, the Cereja River is another important potential pollution source. This 4 km-long river course crosses Bragança, receiving the input of domestic, commercial and hospital sewage directly from existing outfalls, which are later released into the upper sector of Caeté Estuary (Guimarães et al. 2009).

According to existing data, population dynamics and associated economic activities do not show significant temporal variations, which could be reflected in variations in the total amount of sewage released to the estuary. In this sense, the pressure associated with human activity in the estuary can be considered as reasonably steady during any climatic year.

5.2 Natural forcing

In addition to the above mentioned nutrient source, the intrinsic characteristics of the Caeté Estuary, such as its location within the world's second largest mangrove region, which encompasses an area of 8,900 km^2, can contribute to the nutrient balance. It is well known that mangrove forests exchange materials with the surrounding environment (estuary or coast) through tidal inundation. As a result of this, they usually tend to export nutrients (Woodroffe, 1992; Dittmar and Lara, 2001; Dittmar et al. 2006)

In this case, the increase of the tidal range during spring tides enhances the inundation of the mangrove forest along the margins of the estuary. This inundation promotes the release of nutrients from mangrove sediments to the water column, and as a consequence, should induce an increase in nutrients. According to Dittmar and Lara (2001) and Adame and Lovelock (2011), the outwelling of nutrients and organic matter from mangroves measured at the Caeté Estuary (5.0 gN m^{-2} $year^{-1}$) usually exceeds values recorded in mangrove forests in other regions of the world (e.g. Conn Creek in Australia: 1.2 gN m^{-2} $year^{-1}$; Lobos Bay in Mexico: 1.8 gN m^{-2} $year^{-1}$; see Ayukai et al. (1998) and Carrillo et al. (2009) respectively). Although this is a natural contribution to nutrient concentrations in the estuary, when it is added to the anthropogenic input both can synergistically induce a negative impact on the environmental quality of an estuary (measured in terms of nutrients concentration). This normally occurs when the estuary is more susceptible to "retaining" the nutrients (e.g., the dry season).

To put in perspective the present and future role of mangrove outwelling in the eutrophication process, it has to be considered that the extension and quality of mangroves in the area is subject to temporal changes (e.g. Saint-Paul and Schneider, 2010). As an example, Lara et al. (2010) detected a loss of 19 km^2 of mangrove surface during the period 1972 to 1997. However, in a smaller scale analysis, these authors also observed a gain of 3.1 km^2 in the middle sector of estuary during the period 1990 to 1999. To assess the potential consequences of these changes on nutrients release to the river, the evolution of mangroves needs to be monitored, and specially, the extension of the flooding area.

Contrary to what has been observed in other estuaries such as the Nile or the Patuxent (Nixon, 2003; Boynton et al. 2008), the river discharge from the Caeté basin contributes to the dilution of effluents released into the estuary, mainly during the wet season when the river runoff is the highest. According to the data recorded in the Caeté Estuary, an average monthly river discharge of about 45.0 m^3/s or more can be considered to be the threshold to converting river flow into an efficient mechanism that significantly reduces the impact of released effluents.

This larger dilution capacity of sewage effluents observed during the wet season possibly occurs due to the low level of human activities in the hydrographic basin (other than those observed along the estuary itself in Bragança), which would not be expected to significantly affect the water quality of the basin. Regarding this dilution capacity, Gorayeb et al. (2008) showed that along the Caeté hydrographic basin, nutrient levels are very low (nitrate-NO_3 < 2.0 µm, nitrite-NO_2 < 0.2 µm, and phosphate-PO_4 < 0.2 µm). Within this context, it ought to be mentioned that a change in land use in the drainage basin due to an excessive increase in occupation (and corresponding human activities and uses) should modify this factor, producing a surplus of nutrients as has been observed in other areas (e.g., see Noriega and Araújo, 2009).

During the dry season, the river runoff decreases, and it is not as efficient in diluting the effluents as it is during the wet period. Consequently, the nutrients and coliforms concentration increases in the estuary. This also serves to identify the high vulnerability of the system to climatic fluctuations, such as the El Niño phenomenon, which induces droughts in the area through teleconnections (e.g., see Marengo et al. 2008).

The impact of this lower dilution of discharged effluent is most pronounced in the region surrounding the urbanized zone (Bragança city, upper estuary). During this period, the concentration of thermotolerant coliforms was 5 times the maximum value for water permitted for human uses, and it also exceeded the recommended limit for effective conservation of aquatic life, according to the CONAMA criteria (Resolution nº 274/2000).

6. The management perspective

This study has shown that the water quality status in the Caeté Estuary is the result of a combination of factors where the human dimension is clearly dominant. This apparent causal chain between human forcing and environmental risk makes the DPSIR (Driver, Pressure, State, Impact, Response) framework a useful tool to identify different measures to improve the current situation. The DPSIR (OECD, 1993) is an analytical framework to analyze environmental problems by identifying the links between socioeconomic drivers, exerted pressures on the environment, resulting state of the environment, induced impacts and, societal responses to combat the problem. It has been largely used in the analysis of environmental problems in general and in water quality related issues in estuarine and coastal environments (e.g. Borja et al. 2006; Zaldivar et al. 2008; Garmendia et al. 2012). Here this tool is used as a guide for proposing potential management measures to improve the system.

Figure 7 illustrates the application of the DPSIR framework to analyze potential measures to be implemented in the Caeté Estuary. As can be seen, potential measures to mitigate/solve the environmental problem vary significantly in type depending on the target.

<Insert Figure 7>

As has been previously mentioned, the major driver controlling the analyzed environmental problem is the urban development around the estuary, especially Bragança city. This identification is an important issue since, for instance, according to European policies the primary focus of the DPSIR decision-making framework should be on driving forces (Rovira and Pardo, 2006). In this sense, the main type of measures to act on this *driver* is essentially proper urban development planning. However, at present, the city and small settlements already exist, so these measures would not be very effective. In spite of this, they could help to control further increases in sewage discharges into the estuary caused by ongoing urban growth. In this sense, it will be necessary to strictly regulate the occupation and development of new settlements in the near future, as laid out in the city's master plan (Municipal Law nº 3875, Bragança, 2006). The responsibility for the implementation of these measures rests with the Urban planning and Infrastructure Departments of the

Bragança municipal administration, which must guarantee the inclusion of systems for the recovery and treatment of the domestic and industrial effluents produced by new settlements. Again, it is important to stress that although this measure will not solve current problems, they will avoid the increase of untreated effluents into the estuary.

Another potential response is to directly act on the discharge of untreated effluents (*pressure*), which is responsible for the water quality deterioration in the upper estuary, principally during the dry season. In this case, the type of measures are related to building proper infrastructure and would require the construction of efficient sewage treatment systems to avoid the input of untreated effluents into the estuary. Ideally, this should include a sewage system collecting all wastewater and a treatment plant. At present, the responsibility for the treatment of domestic effluents rests with the Pará State Sanitation and Water Supply Company (COSANPA). In the short-term, this response is not likely to be effective since there is currently no public sanitation system in the municipality and these works likely would take decades to complete. In spite of this, it is compulsory to immediately start to implement these types of measures because they would provide a definitive solution for untreated wastewater release into the Caeté Estuary.

The release of untreated sewage into aquatic environments is strictly forbidden in Brazil by resolution number 357/2005 (article 24) of the National Environment Council (CONAMA), and in Pará by state Law nº 5887/1995 (Pará, 1995). However, this work has shown that despite the existence of these laws, the *state* of the water in the Caeté Estuary is adversely affected by the existence of these effluents. Thus, the estuary has experienced episodes of eutrophication and microbiological pollution.

While management measures can be applied, they will probably not solve the environmental problems of the Caeté estuary directly, given that in most, if not all cases, they will do no more than monitor the quality of the estuary's water. In this context, the current lack of any systematic monitoring of the water quality by local authorities and the complete absence of any effective punishment for infractions surely contribute to the ongoing contamination of the Caeté Estuary.

Finally, when measures are directed to mitigate the identified *impacts*, which essentially are on economic activities dependent on water resources such as fishing, aquaculture and agriculture, they will be related to *regulation*. This implies the need to establish some limits and restrictions for water use depending on the current water quality. This is already regulated by CONAMA and its application to the recorded values indicate that those uses demanding high water quality, such as bathing and domestic use, should be prohibited during some seasons. Of course, to effectively implement this, an efficient monitoring program encompassing different sectors of the estuary will be required to guarantee the effective evaluation of water quality. This program should include the monitoring of indicators such as ammonia and biochemical oxygen demand (BOD) in addition to those included in the present work (nitrite, nitrate, phosphate, thermotolerant coliforms and chlorophyll *a*).

In any case, this regulation should consider specific characteristics of Amazon waters (high concentrations of dissolved nutrients and chlorophyll *a*) and fluctuations in the freshwater discharge associated with seasonal rainfall variations, events of equinox spring tides and other phenomena such as El Niño events.

7. Final consideration

A comparison between values observed at the Caeté Estuary with similar environments (the Amazon region, macrotidal regions, or equatorial environments) demonstrated that observed values of nutrient concentrations in the middle and lower sectors correspond to those expected in the Amazon region reported by Lam-Hoai et al. 2006 (nitrite-NO_2 + nitrate-NO_3 between 0 and 21.0 µm and phosphate-PO_4 between 0 and 0.5 µm) and Pamplona et al. 2013 (nitrite-NO_2 predominantly lower than 3.0 µm and nitrate-NO_3 lower than 15.0 µm). However, the high quantity of nutrients and chlorophyll *a* observed in the upper sector does not correlate with the expected amount for regions with low industrial development and low population density. These values are similar to those found in other Brazilian estuaries subject to intense discharge of domestic and industrial effluents, such as the Pina basin and Tejipió river (frequent values of nitrite-NO_2 from 1.2 to 4.3 µm, nitrate-NO_3 from 1.7 to 29.0 µm and phosphate-PO_4 2.8 to 6.7 µm, Nascimento et al. 2003). They are also similar to values found in highly humanized areas such as the Recife and the Massangana harbors (chlorophyll a concentrations between 1.0 and 20.0 mg/m^3; Flores-Montes et al. 2011, Alves et al. 2013; Cotovicz et al., 2013).

In the Caeté Estuary, the high level of fecal coliforms found in the upper sector is indicative of the relevance of human influence (e.g., sewage effluents), and its potential contribution to the estuary eutrophic status. However, the eutrophication status observed in the middle sector may be essentially considered to be a natural process, since low coliform concentrations should be indicative of a significant decrease in human influence.

Yet the Caeté river basin has a low population density and a low industrial development, so human pressure can be considered to induce a moderate impact. The concentration of the population and the centralization of economic activities in the upper sector of the estuary, combined with the influence of a harbor, applies a considerable local pressure in this sector, with the potential risk of exporting their effects downstream.

Assuming that the population grows about 20% per decade in the region, which leads to an increase in human impacts in the area, it is important to implement a monitoring program that will evaluate pressures and corresponding impacts on the estuary before it becomes affected in an irreversible way.

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Figure

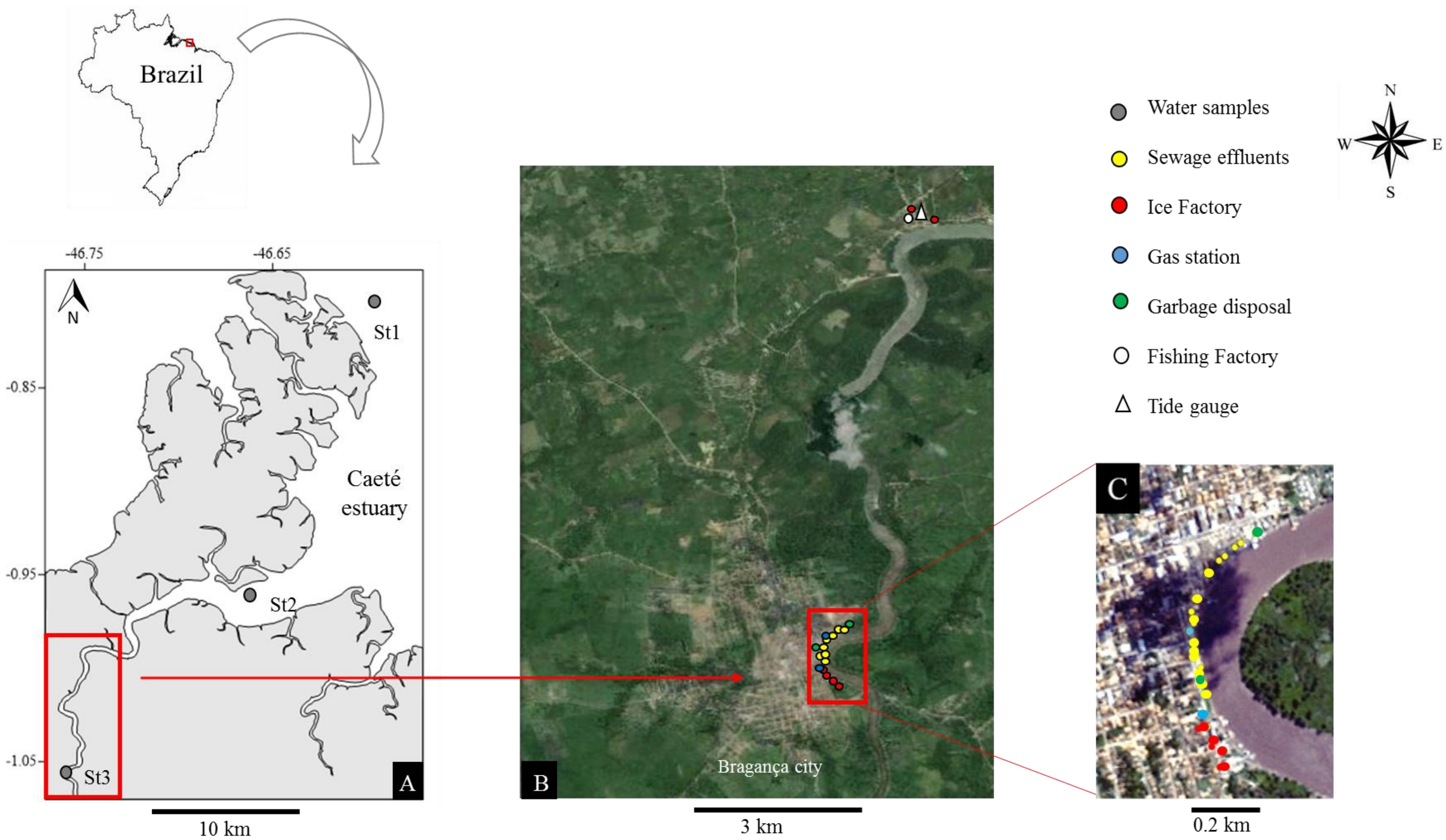

Figure 1: Caeté estuary (A), Bragança city (B) and pollution sources (C) along the estuary.

Figure

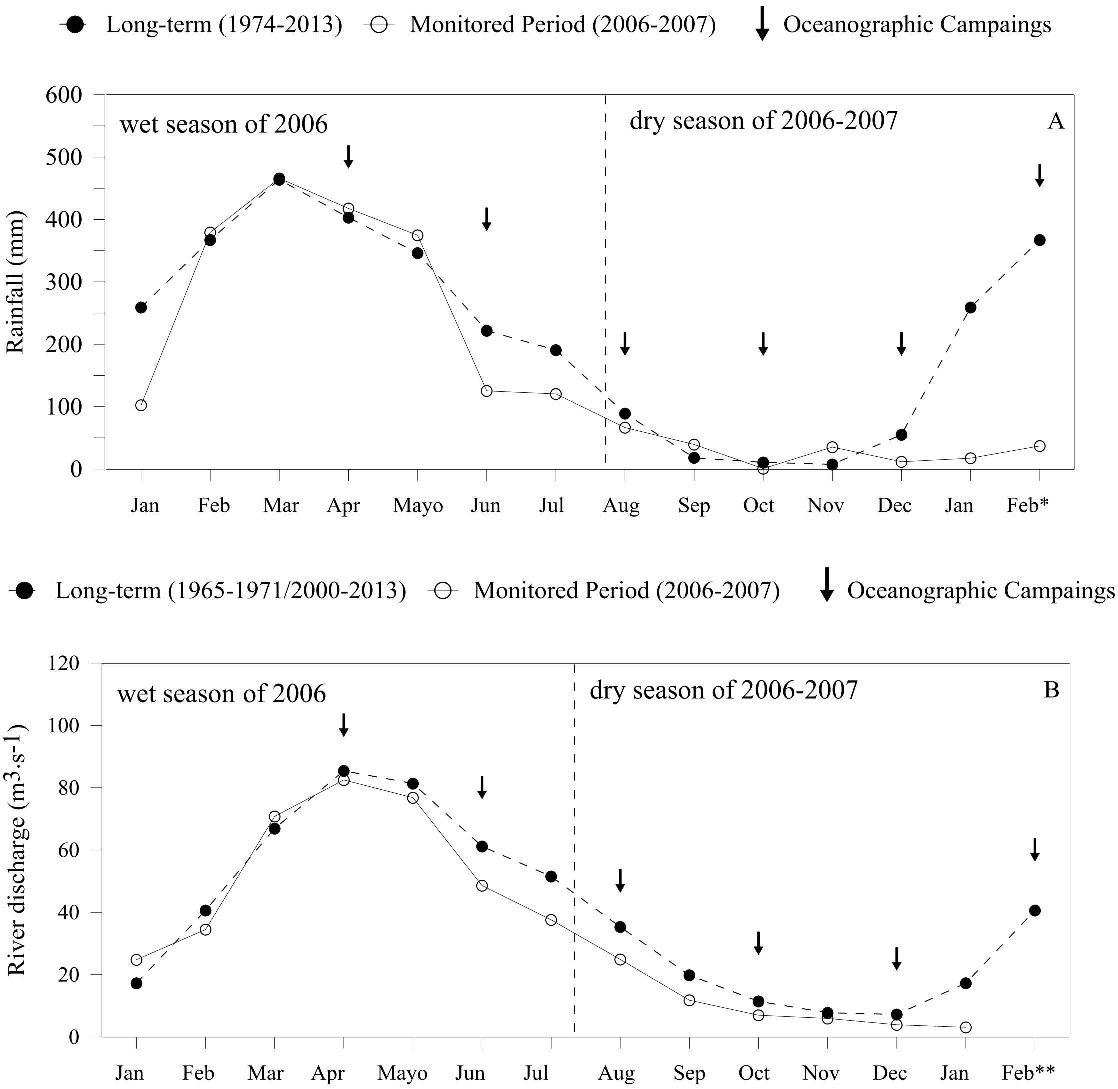

Figure 2: Rainfall (A) and Caeté River discharge (B) data measured upstream of Bragança city during the monitoring period (Source: INMET and ANA). (*) Cumulative rainfall until the data campaign. (**) Not available data.

Figure

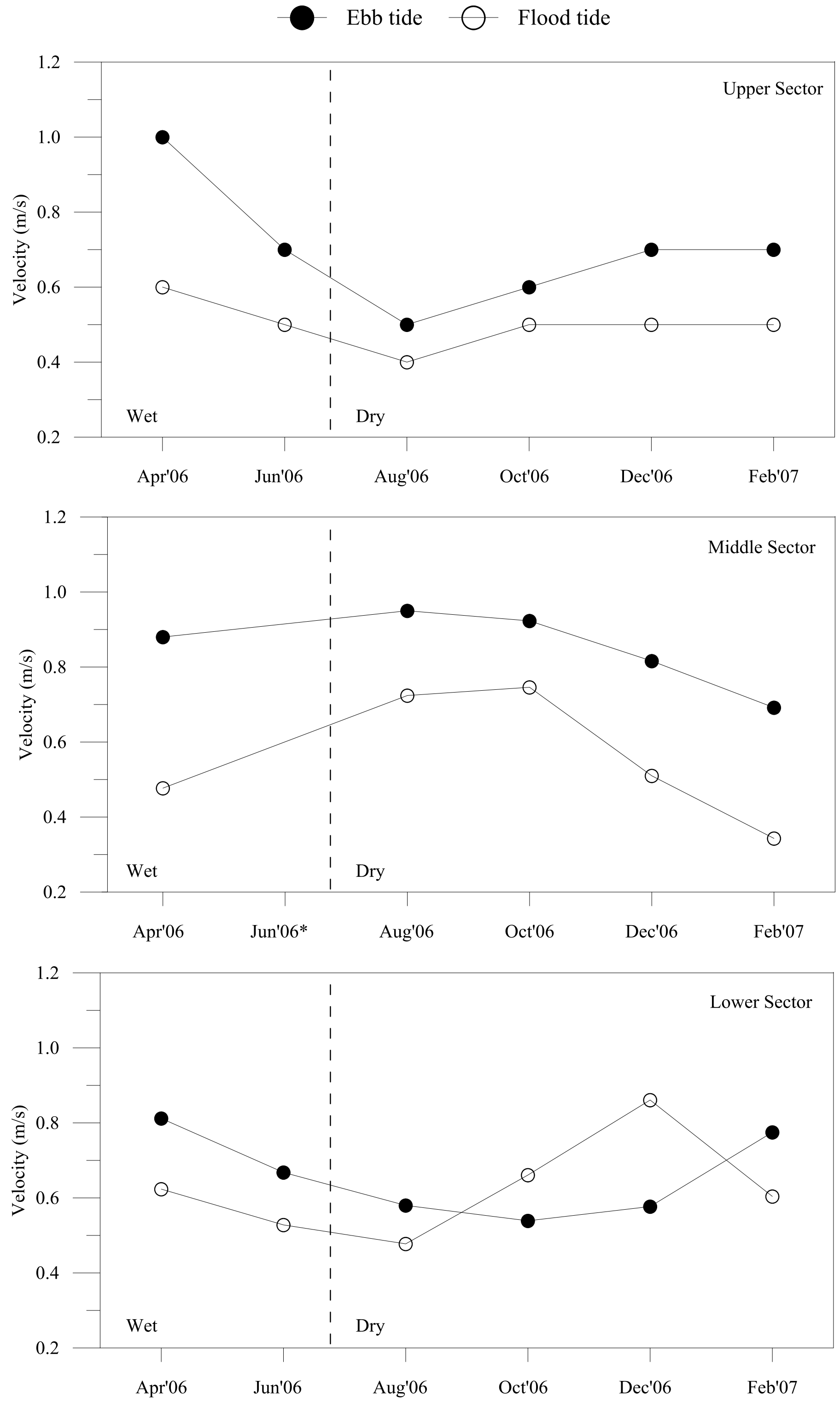

Figure 3: Mean current speed during monitoring period in the upper, middle and lower sectors of Caeté estuary. (*) Data not collected.

Figure

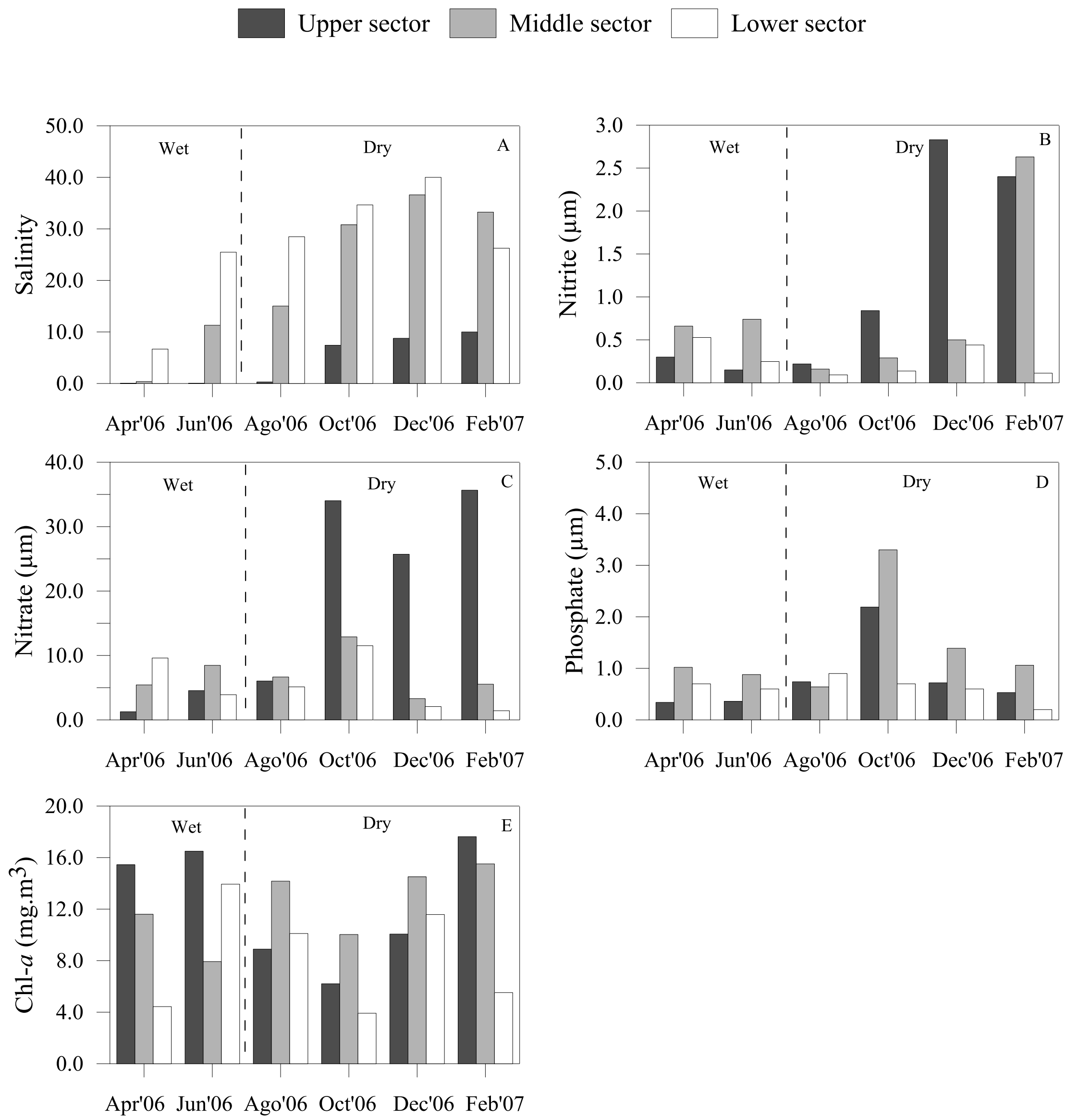

Figure 4: Variation of salinity (A), nitrite-NO_2 (B), nitrate-NO_3 (C), phosphate-PO_4 (D) and chlorophyll *a* (E) concentrations in the upper, middle and lower sectors in the Caeté estuary.

Figure

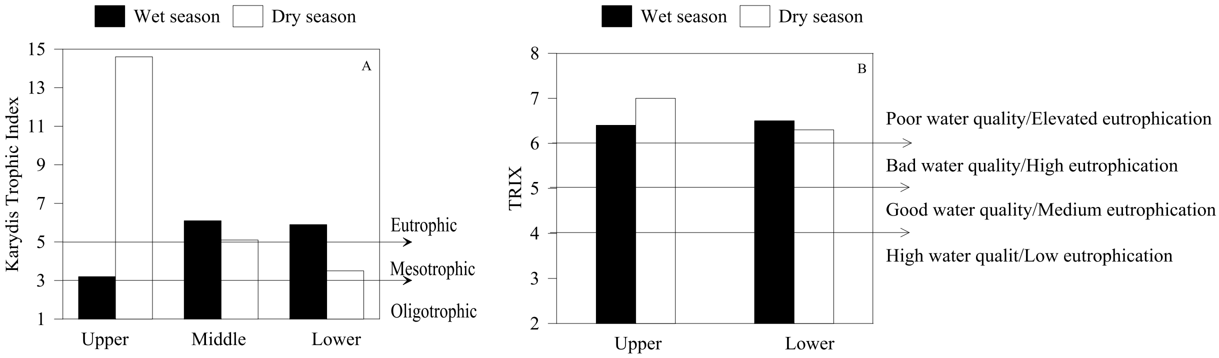

Figure 5: Trophic status of Caeté estuary. A: Index developed by Karydis et al. (1983) and B: TRIX developed by Vollenweider et al. (1998).

Figure

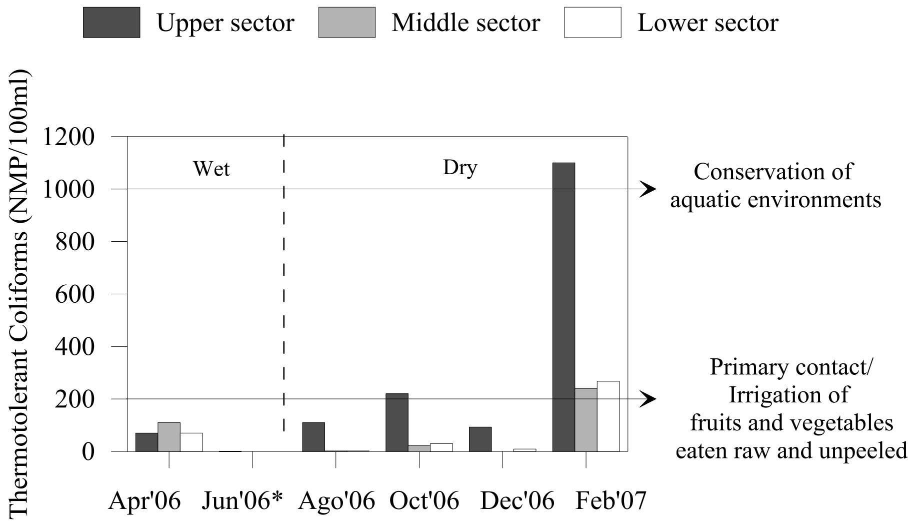

Figure 6: Variation of thermotolerant coliform concentrations in the upper, middle and lower sectors in the Caeté estuary. (*) Data not collected.

Figure

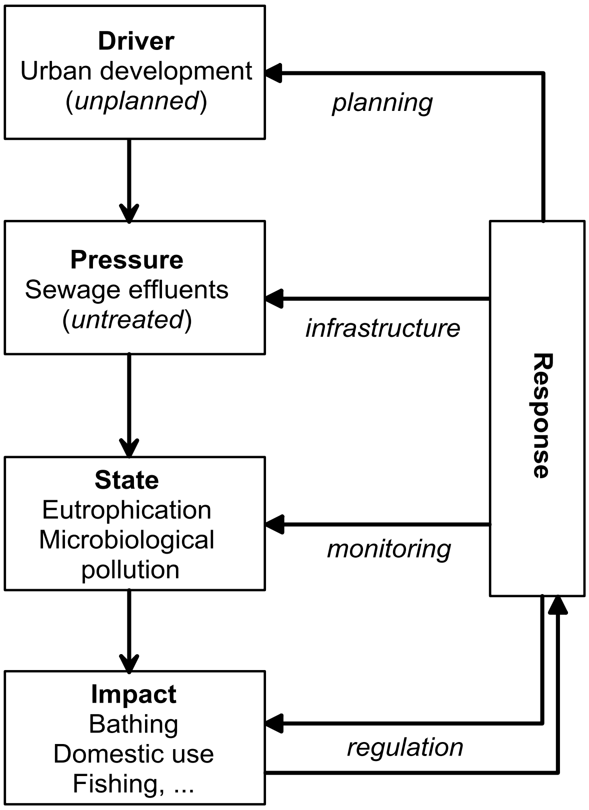

Figure 7: The DPSIR framework applied to the Caeté estuary.

Table

Table 1: Estimative (tonnes) of BOD and dissolved nutrients discharged daily from GPresca commercial Ltda in the Caeté estuary.

	Discharge point	
	Min	Max
BDO (mg)	1,50	21,20
Total phosphorus (µm)	0,00	0,57
Nitrate (µm)	0,21	0,54
Nitrite (µm)	0,00	0,11
Ammonium (µm)	0,07	6,80